VIBRATION METHOD FOR TRACKING THE RESONANT MODE AND IMPEDANCE OF A MICROWAVE CAVITY

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ABSTRACT

We have developed a vibration technique to continuously maintain mode resonance and impedance match between a constant frequency magnetron source and resonant cavity. This method uses a vibrating metal rod to modulate the volume of the cavity in a manner equivalent to modulating an adjustable plunger. A similar vibrating metal rod attached to a stub tuner modulates the waveguide volume between the source and cavity. A phase sensitive detection scheme determines the optimum position of the adjustable plunger and stub tuner during processing. The improved power transfer during the heating of a 99.8% pure alumina rod was demonstrated using this new technique. Temperature-time and reflected power-time heating curves are presented for the cases of no tracking, impedance tracker only, mode tracker only and simultaneous impedance and mode tracking. Controlled internal melting of an alumina rod near 2000°C using both tracking units will also be presented.

INTRODUCTION

In recent years, there has been a concerted effort to improve the microwave heating technique for processing materials at high temperature [1]. Improved optimization of the energy transfer from a microwave source to the material being processed is required in many applications before the microwave heating technique will become commercially competitive. The most important factors that limit the transfer of energy to the material are the detuning of the microwave cavity resonance and the impedance match between the microwave source and microwave cavity as the material is heated. These detuning effects are associated with the temperature dependent variation of the complex dielectric constant of the material during processed. In the case of the impedance match, a variation in the imaginary component of the dielectric constant causes a change in the cavity load as seen by the power source driving the cavity. The variation in the real part of the dielectric constant is primarily responsible for a similar change in the cavity resonance.

For a constant frequency microwave source, such as a magnetron, correcting for variations in the cavity resonant frequency generally requires the use of a mechanical plunger to adjust one of the microwave cavity dimensions. By changing the cavity dimension during processing, one can attempt to continuously tune the cavity resonance to the fixed frequent y source. The problem is that manual adjustment of the plunger is generally not an efficient method to control the microwave processing of the material.

Impedance matching between a microwave source and applicator load has been accomplished in the past by either manually adjusting the position or shape of the excitation coupler at the cavity (adjustable iris method) or manually changing the phase of the incoming microwave energy using stub tuners (phase shifter method) [2], [3]. There are many cases where the rate of change of the cavity load during microwave processing is so fast that manual adjustment is too slow to maintain impedance matching. The lack of maintaining a resonance and impedance matching can lead to a significant reduction in the power transfer to the material being processed. This is particularly true for low absorbing materials where the resonance is very sharp, i.e., the cavity has a high quality factor, Q. An efficient <u>automatic</u> method for tracking the cavity resonance and impedance match would significantly improve the microwave processing of low loss materials starting from room temperature.

We have developed and tested a new vibration method that optimizes microwave power transfer to a material being processed. This optimization process allows a much larger class of materials to be heated to higher temperatures. These new capabilities should enhance the development of economical commercialization processes using microwave heating.

RESONANT FREQUENCY TRACKER

A standard approach for tracking a resonance is to frequency modulate the carrier signal. In this approach, the modulation in the drive signal leads to a modulation in the electric field in the cavity [4]. By demodulating an electric field sensor signal, one can determine the direction needed to shift the. frequency of the source back to the resonant condition. This method works very satisfactorily for microwave sources that are broadband, such as a Traveling Wave Tube (TWT) source. In most processing applications, however, a fixed frequency magnetron source is used.

Our solution for a fixed frequency source was to find an alternative approach to modulate the electric field in the cavity. This can be accomplished by using a vibrating recta] rod excited by a loudspeaker. The rod protrudes into the cavity through a hole in the wall. The vibrating rod modulates the volume of the cavity which is equivalent to modulating the plunger. The most effective location for the entrance hole corresponds to a position of maximum electric field strength. This position will depend on the microwave mode being excited. For our prototype system, we used a TE_{102} mode in a WR 284 waveguide cavity as shown in Fig. 1. The vibrating rod was placed at a quarter of the way along the cavity which corresponds to a maximum electric field line for this mode. A depth adjustable diode crystal detector that monitors the relative power level associated with the electric field was also placed along the same maximum electric field line at the opposite wall from the rod.

An oscillator drove the loudspeaker at a low modulation frequency in the range $30 < f_1 < 100$ Hz. A hollow, low mass, metal cylindrical rod was attached to the loudspeaker cone and its tip inserted ≈ 0.6 cm inside the cavity. The detected low frequency modulation of the electric field obtained by the diode was sent to an amplifier and then to a multiplier unit. The multiplier combined the driver and receiver signals to obtain their product. By saturating the amplitude of both signals, the output of the multiplier only depended on the phase between the signals. This output was then rectified and amplified before controlling the forward or backward motion of a motor attached to the plunger. The phase relationship between the driver and receiver signals determined which direction the plunger should move.

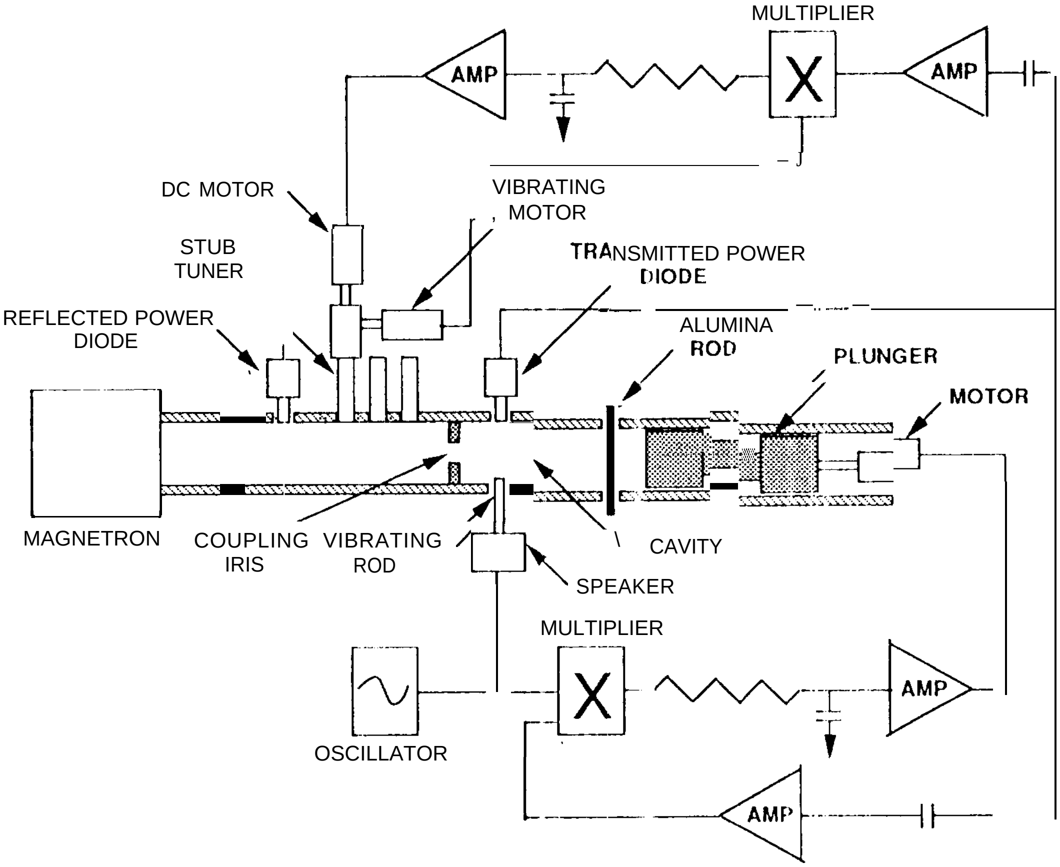

Fig. 1 Schematic of the microwave system and phase sensitive detection schemes used in the vibration tracking method.

IMPEDANCE MATCHING TRACKER

The apparatus used in the impedance matching technique is also shown schematically in Fig. 1. For this prototype system, we again used a TE_{102} mode waveguide cavity. When the power source is ideally critically coupled to the cavity, all the microwave energy is transmitted to the cavity and thus the transmitted power diode signal is maximum and the reflected power diode signal is zero. We used an ac motor driving an eccentric crank on its shaft to modulate the stub tuner. This modulation amplitude remained constant with its value being determined by the displacement of the eccentric. The modulation frequency, f_2, was controlled by the motor speed and could be varied from $0 < f_2 < 12$ Hz. The modulation frequency was measured using a light sensitive diode positioned to view a shiny surface, attached to the motor shaft, that oscillated through the diode field of view. A phase sensitive detection technique, similar to the one used to track the cavity resonance, is shown schematically in Fig. 1. By comparing the phase relationship between the modulation source and transmitted or reflected power diode signals, one could determine whether the stub tuner was above or below the optimum time averaged position for impedance matching. If the position of the stub tuner was not optimized, a positive or negative dc signal was generated to control a motor that could move the time averaged position of the vibrating stub tuner up or down. One advantage of using the reflected power diode is that it more strongly senses the stub tuner modulation than the transmitted power diode, especially at high temperatures where the field strength in the cavity is weak. The reflected power diode also more weakly senses the mode resonance modulation and thus essentially decouples the two modulation signals.

RESULTS AND DISCUSSION

The versatility of these tracking techniques was demonstrated by heating a 0.63 cm diameter, Vesuvius McDanel Company, 99.8% pure alumina rod. Before each heating test, we optimized the stub tuners and plunger position at room temperature. A constant 200 watts of forward power was used for all the tests. The first heating test was performed with both the impedance and resonant mode trackers off. An Everest IR noncontact thermometer, with a range of O - 11 00°C, measured the surface of the rod half way down in the cavity. Figure 2 shows the sample temperature and reflected power as a function of time. As the sample temperature rose, both the impedance and resonant mode mismatch occurred. Since the detuning of the impedance and mode resonance both depended on the temperature dependence of the complex dielectric constant, the sample temperature climbed asymptotically to a maximum temperature of ≈ 470°C. This maximum temperature depends on a balance between the degree of detuning and the corresponding reduction of power transmitted into the cavity. We see that the reflected power, which is dissociated with both the impedance and mode resonance detuning became very large reaching an asymptotic value of ≈ 160 watts. The initial drop in reflected power at the beginning of this test was associated with a slight initial detuning of the system.

in the next test, only the resonant mode of the cavity was continuously tracked and adjusted to match the magnetron frequency. A modulation frequency of 30 Hz was used with this mode tracker. By tracking the resonant mode, we eliminated any reduction in power transfer to the material (and increase in reflected power) primarily due to changes in the real part of the dielectric constant. Figure 3 again shows the sample temperature and reflected power under these conditions. Because of the higher temperatures measured in this run, we made a second measurement of

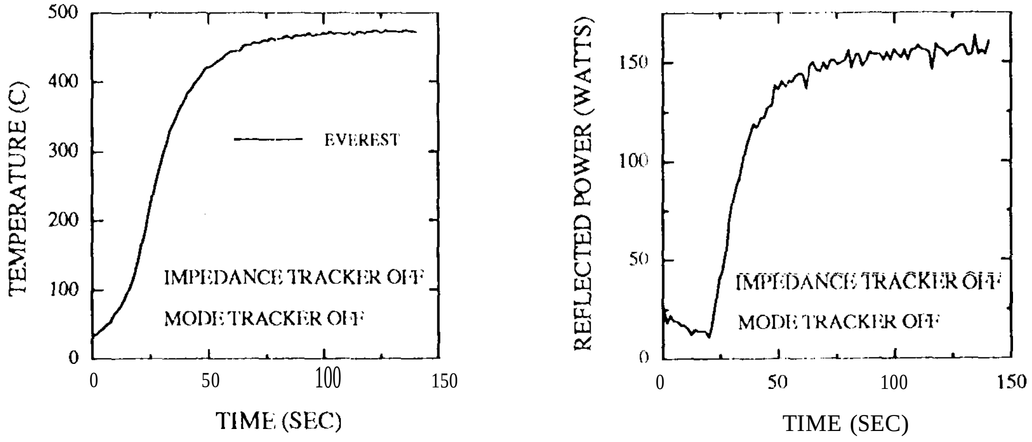

Fig. 2 Temperature and reflected power heating curves with both vibration tracking units off.

the sample surface on the opposite side from the Everest (dashed curve) using an Accufiber pyrometer thermometer (solid curve) with a range 500- 2400°C. We see that by using the plunger mode tracker the maximum temperature reached was ≈ 1255°C. Also, the reflected power increased to ≈ 90 watts which is much less than with no resonant mode tracker (see Fig. 2). We assume that this 90 watts is associated with the impedance detuning that is still present. By comparing the maximum reflected values obtained in Figs. 2 and 3, we deduced that the detuning of the resonant mode caused ≈ 70 watts of reflected power for the present configuration.

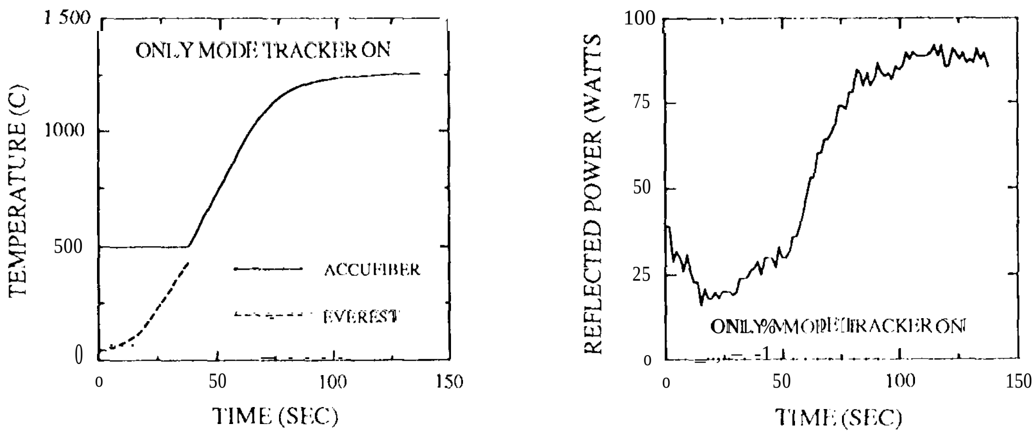

Fig. 3 Heating curves using only the cavity mode vibration tracking unit.

In the next test, the impedance mismatch between the cavity load and magnetron source was tracked and minimized by motor controlling one of the stub tuners (the most sensitive one). This tracking unit used a modulation frequency of 6.4 Hz.

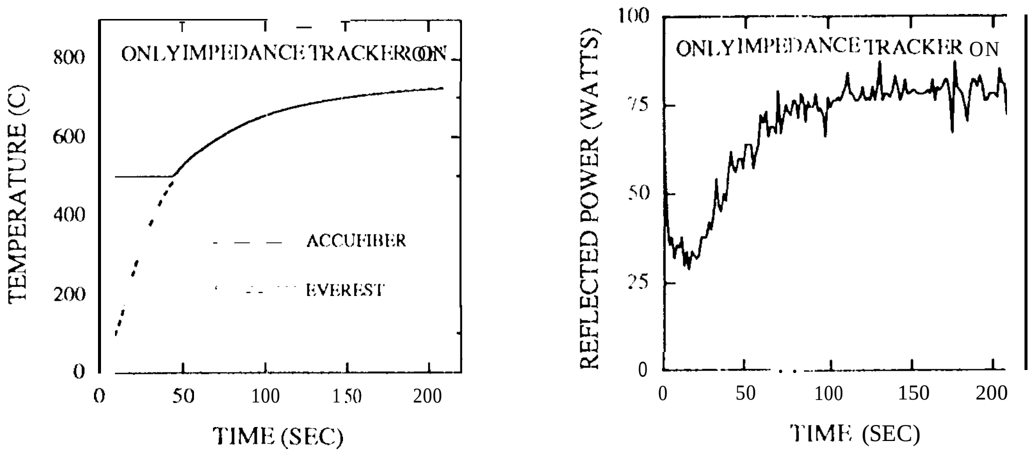

Fig. 4 Heating curves using only the impedance vibration tracking unit.

This frequency was chosen to be significantly different from the 30 Hz of the plunger tracker and not to be a submultiple of that frequency, Again both thermometers were used. Figure 4 shows the sample temperature and waveguide reflected power versus time. The alumina rod initially heated quickly until the cavity mode frequency was sufficiently shifted away from the magnetron source frequency. As this occurred there was a gradual decrease in the transmitted power (increase in reflected power) since less microwave energy entered the cavity to heat the sample. Since this detuning of the impedance depends primarily on the temperature dependence of the complex dielectric constant, the sample temperature climbed asymptotically to a maximum temperature. This maximum temperature depends on a balance between the degree of mode detuning and the corresponding reduction of power absorbed by the sample. This time the sample surface reached a maximum temperature of= 725°C which was lower than the maximum of 1255°C obtained in Fig. 2 using only the resonant mode tracker. By comparing the heating curves of Figs. 2 and 3 we can see that for the present configuration the resonant mode tracker is more important than the impedance tracker for reaching the highest sample temperature. The reflected power reached a maximum of= 80 watts which is consistent with our estimate of 70 watts obtained from Figs. 2 and 3.

Figure 5 shows the sample heating curve and waveguide reflected power when both the stub tuner and the resonant mode vibrating units are in operation. In this test, the impedance tracker was turned on after ≈13 seconds. Thus, during this initial time interval, the reflected power began to increase as the sample temperature increased. The reflected power was returned to a minimum value within ≈ 20 seconds after turning on the impedance tracker. It took ≈ 40 seconds for the sample temperature to reach 500°C after which the sample quickly heated to ≈1440°C within two minutes. The heating rate of the alumina sample also increased significantly to ≈ 20 °C/sec. The reason for the improvement in the peak temperature over the previous tests was that maximum power was now continuously being transmitted into the cavity. The maximum temperature was also enhanced by the fact that the imaginary dielectric constant, ε'', increases with temperature. This increase in ε'' leads to an increase in the microwave absorption in the sample that further tends to heat the sample to even higher temperatures.

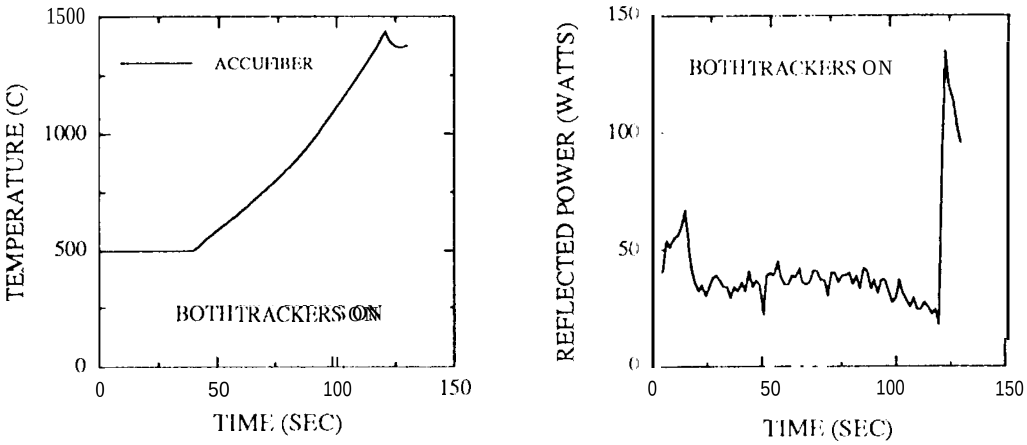

Fig. 5 Heating curves using both the cavity resonance and impedance vibration tracking units.

We see that the. reflected power did not reach zero even with both stub tuner and resonant tracking units on. The resultant 20 watt minimum baseline, occurring at higher temperatures, was probably associated with the detuning of the impedance matching between the microwave source and the cavity due to the other fixed stub tuners.

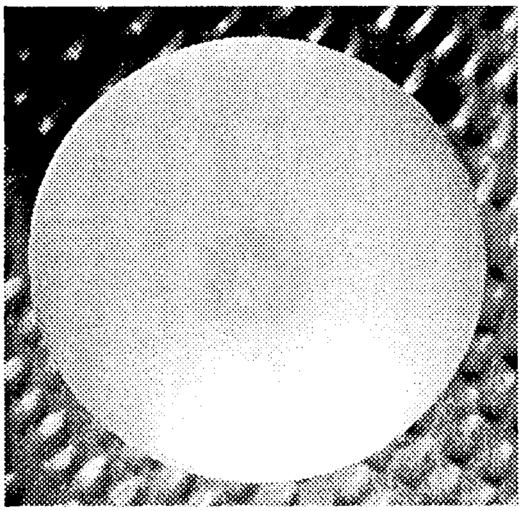

Fig. 6. Cross-section of 0.5 cm diameter rod showing internally melted region.

When the alumina rod reached approximately 1400°C there was a sudden increase in the reflected power leading to a drop in temperature. This phenomenon was associated with the onset of melting inside, the sample. After this heating test, we cut the sample at the position where the temperature was measured and observed an internally melted region as shown in Fig. 6. Since the melting point of this high purity alumina is ≈ 2000 C, there was ≈ 600°C temperature gradient between the surface and center of the sample. This behavior is consistent with the predictions of microwave absorption models [5].

CONCLUS1ON

In conclusion, we have developed a novel vibration tracking technique. This technique was implemented to maintain a frequency and impedance match between a cavity load and magnetron source. With these tracking units in operation, a high purity alumina rod was internally melted within two minutes using only 200 watts of forward power. We successfully demonstrated the tracking of the most sensitive stub tuner for our configuration. Adjustment of up to three stub tuners may be necessary to continuously match the source to the cavity during high temperature processing. The same scheme, using different modulation frequencies, could be used to track the other less sensitive stub tuners if necessary. This in-situ vibration method for tracking the resonant mode anti load impedance should permit enhanced process monitoring and control and lead to the high temperat ure processing of a large number of low microwave absorbing materials that have commercial value.

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